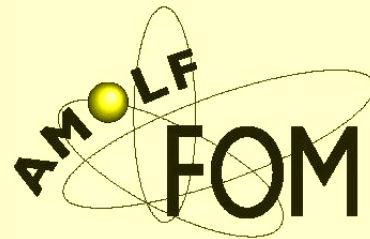


# Low threshold erbium–implanted toroidal microcavity laser

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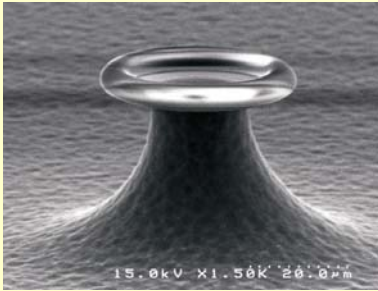
Bumki Min, Tobias Kippenberg, Lan Yang, Kerry Vahala  
Dept. of Applied physics, California Institute of Technology  
Pasadena, USA



# Erbium-doped toroidal microcavity lasers

Microcavity applications: sensing, cavity QED, optical filtering, and low-threshold lasing

## *On-chip toroidal microcavity*



$V=180 \mu\text{m}^3$  at 1550 nm

$Q=10^8$  at 1550 nm

Small mode volume  $V$ :  
lithographic techniques  
reflow of fibers  
microdroplets

High quality factor  $Q = \omega P / (dP/dt)$ :  
low absorption loss  $\text{SiO}_2$  ( $\alpha < 0.2$  dB/km)  
low scattering loss (smooth surfaces)

Efficient tapered fiber coupling:  
single mode to single mode, high coupling  
efficiency ( $\sim 100\%$  for critical coupling)

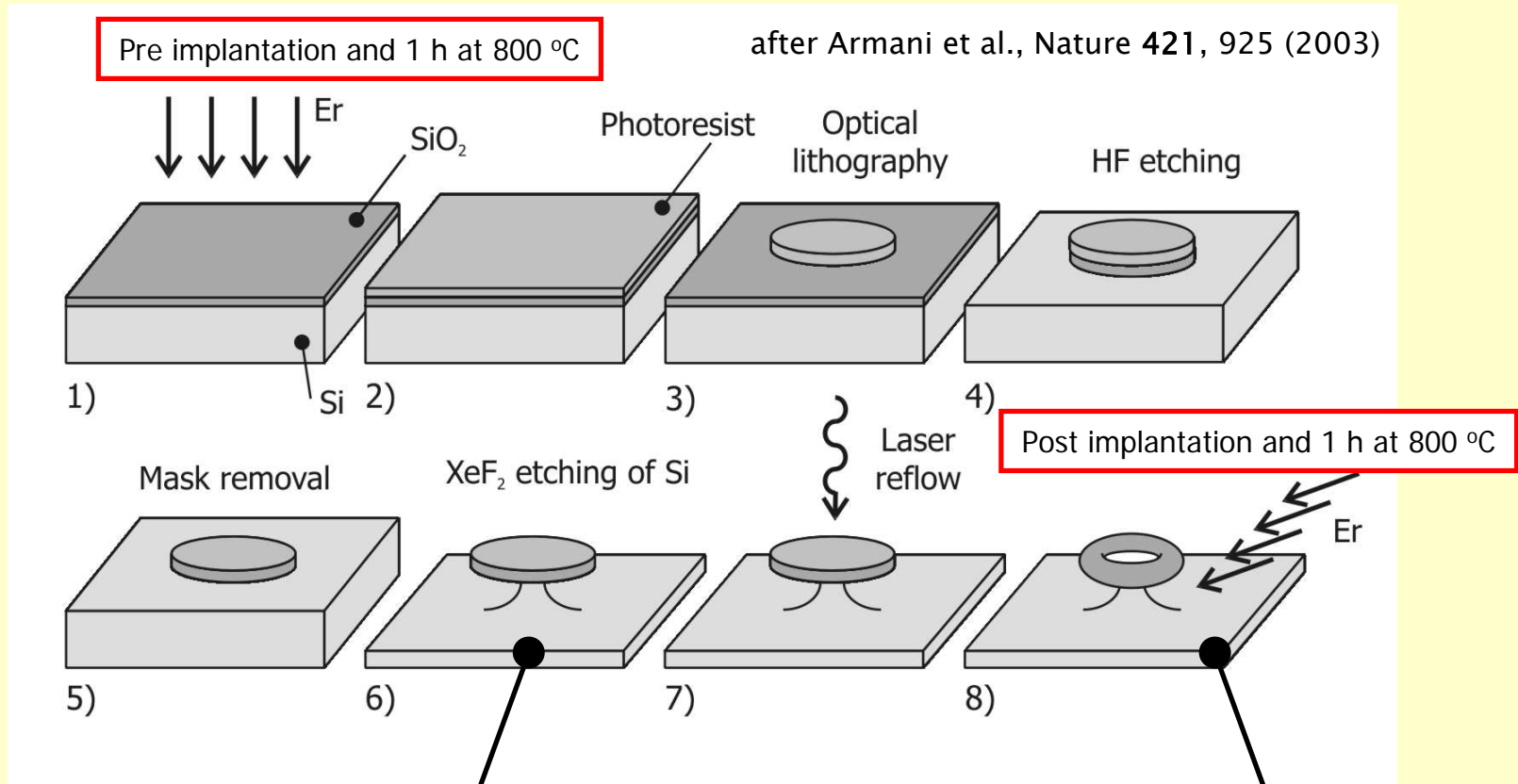
Power enhancement at  
resonant modes

$$\frac{P_{cav}}{P_{in}} = \frac{\lambda}{\pi^2 n R} \frac{Q_{ex}}{\left(1 + \frac{Q_{ex}}{Q_0}\right)^2} \cong 10^5$$

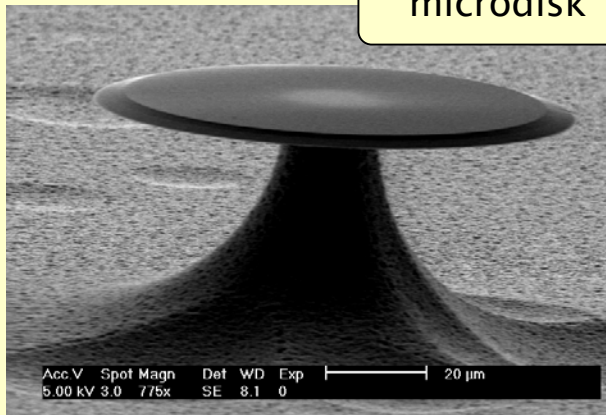
*efficient lasing....*

*Can we fabricate an on-chip erbium-doped  
toroidal microcavity laser with low lasing threshold?*

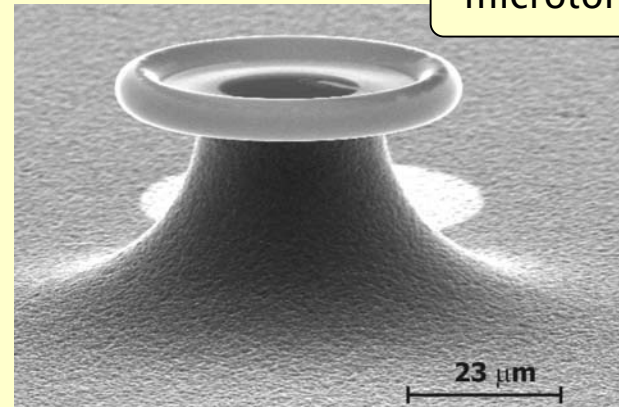
# Fabrication of erbium-doped toroidal microcavity lasers



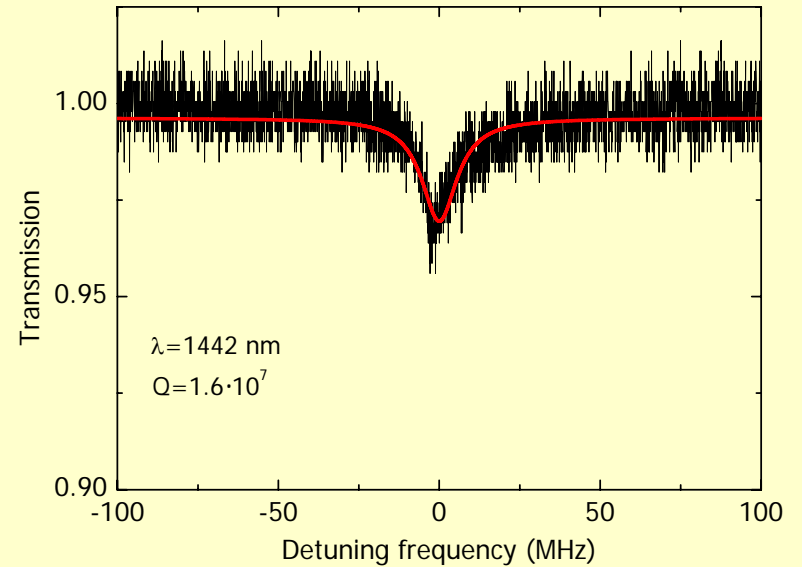
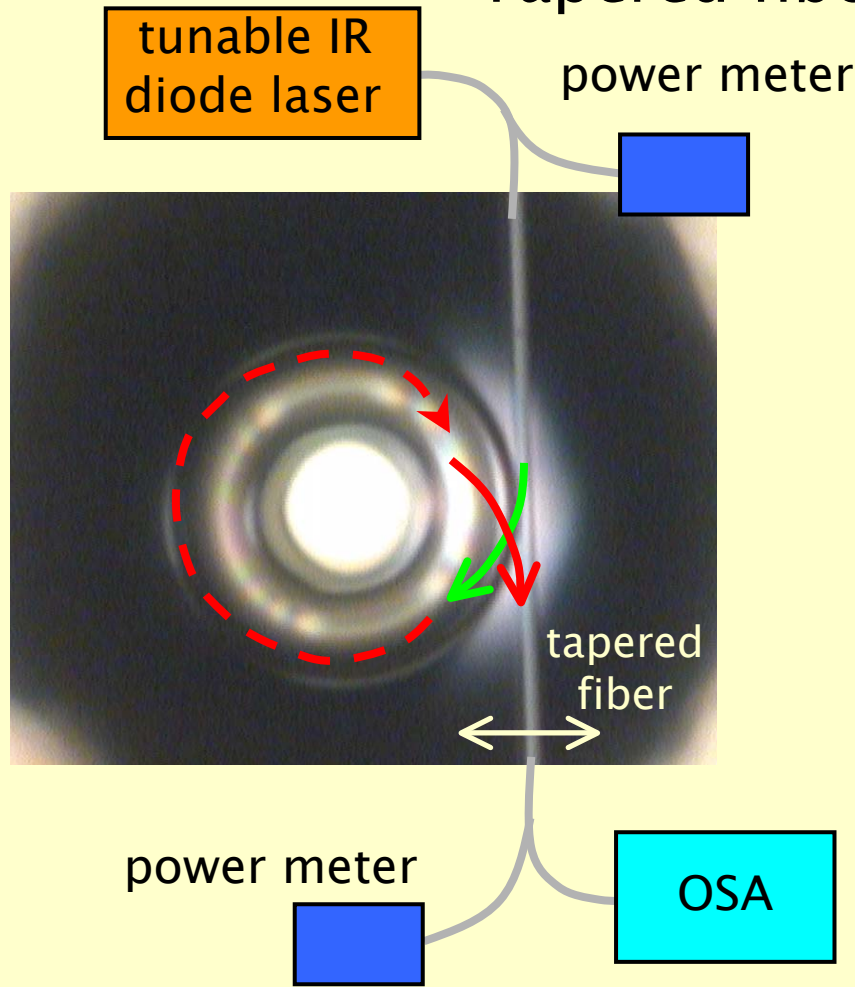
microdisk



microtoroid



# Tapered fiber coupling



$Q_0 = 3.9 \cdot 10^7$  pre implanted

$Q_0 = 1.6 \cdot 10^7$  post implanted

Fabrication maintains high-Q  
 $Q_0$  for the most part due to erbium absorption

# Confocal spectroscopy of erbium doping in microtoroids

Post implanted

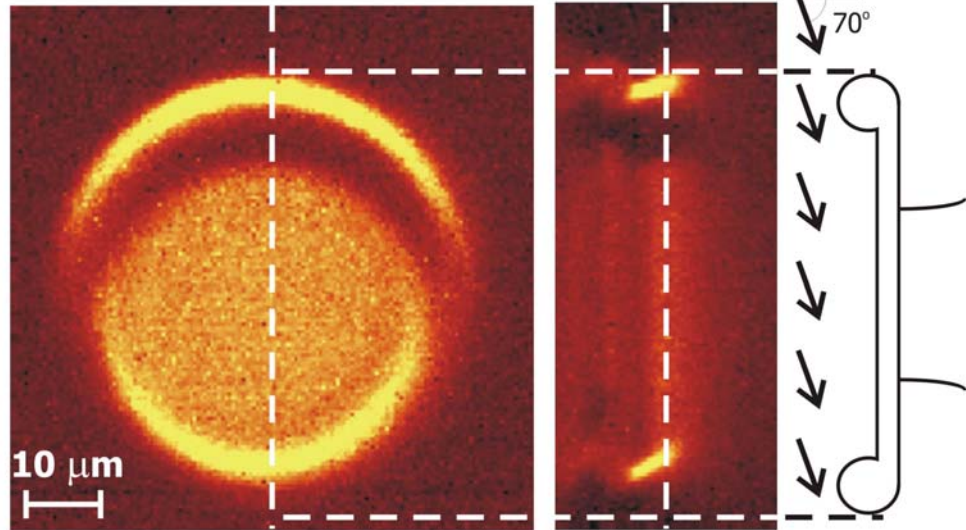
2 MeV Er

$\phi = 4.2 \cdot 10^{15}$  Er/cm<sup>2</sup>

$\lambda_{\text{exc}} = 532$  nm

100 $\times$  objective

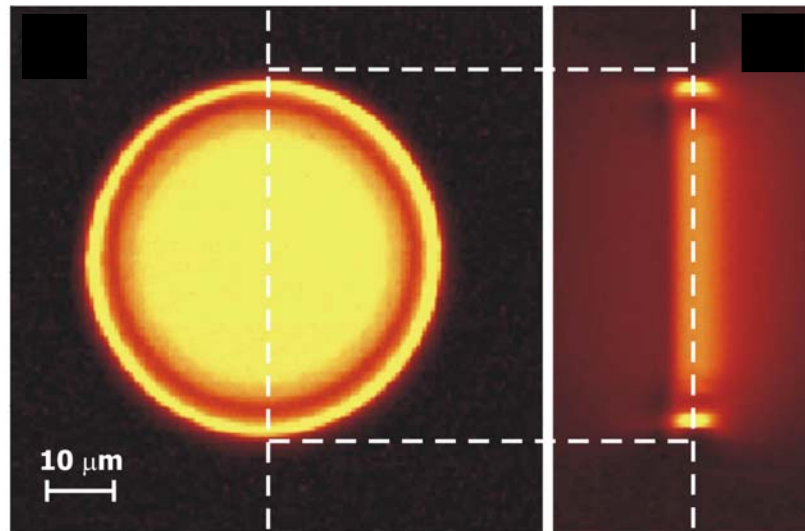
oil immersion



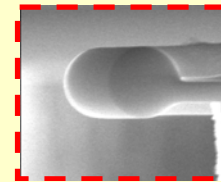
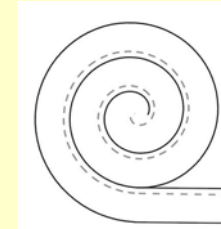
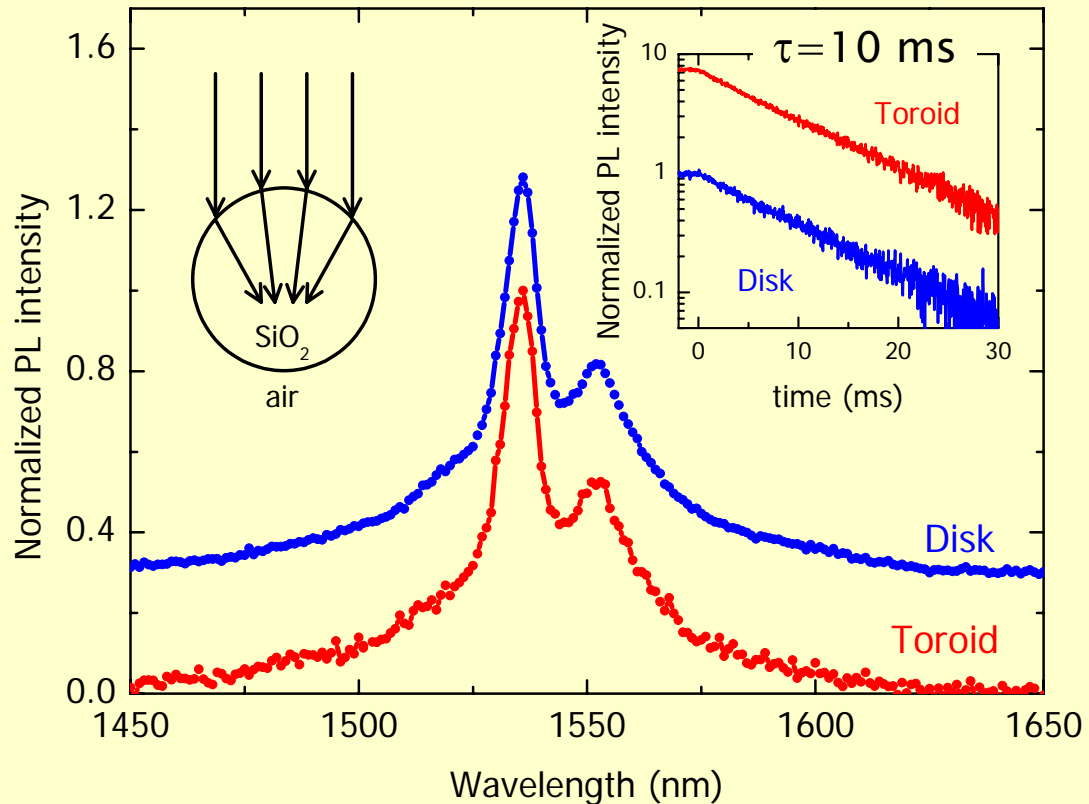
Pre implanted

2 MeV Er

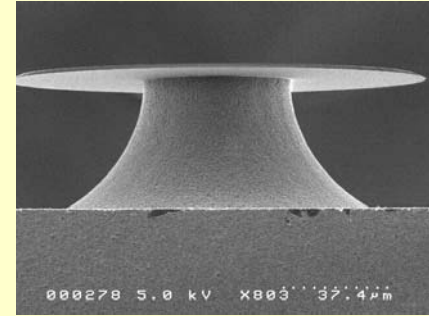
$\phi = 1.2 \cdot 10^{16}$  Er/cm<sup>2</sup>



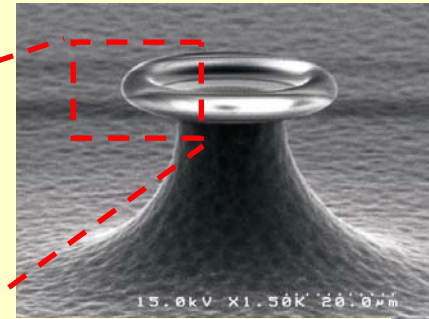
# Far field photoluminescence spectroscopy: pre-implanted microtoroids



Disk



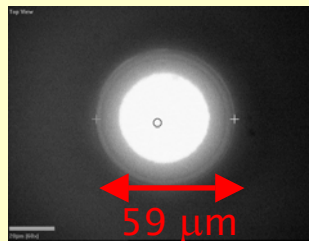
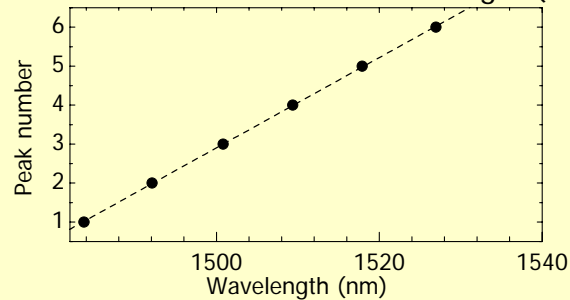
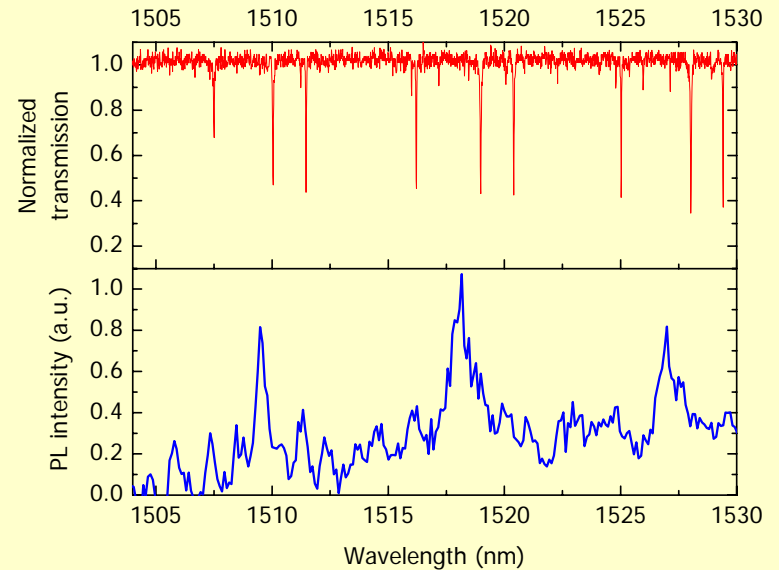
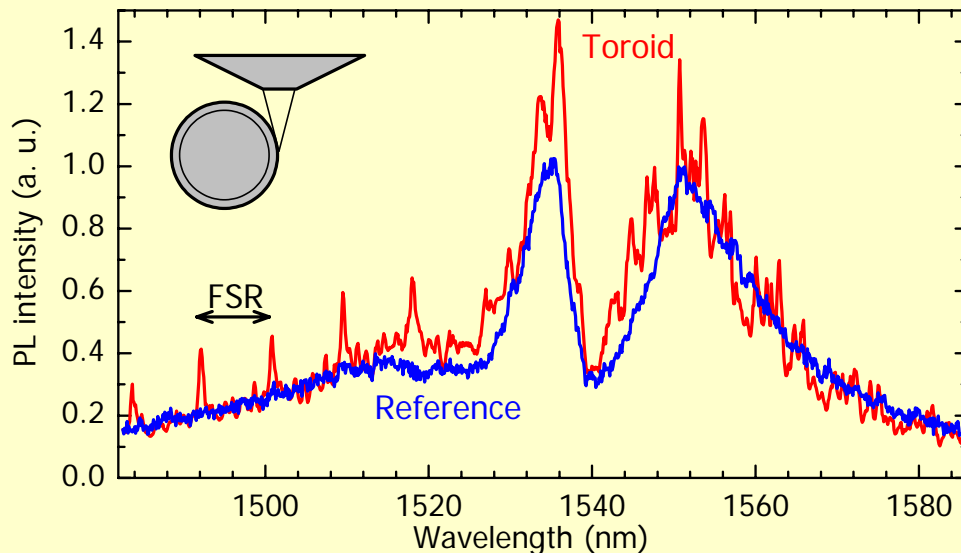
Toroid



- $\tau_{\text{toroid}} = \tau_{\text{disk}}$  : no Er diffusion (otherwise concentration quenching)
  - no Purcell-enhanced decay rate for Er expected –
- No effect of the cavity on the emission spectrum
  1. cavity geometry (refraction)
  2. collection direction (out of plane)
  3. erbium ions are located far from perimeter

# Modified spontaneous emission of erbium

59  $\mu\text{m}$



$$\text{FSR}_{\lambda} = \lambda^2 / 2\pi R n$$

$$\downarrow$$

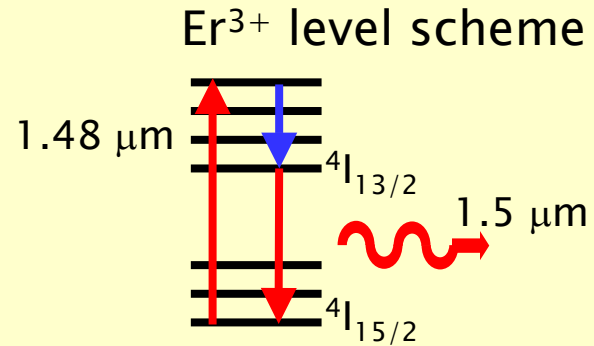
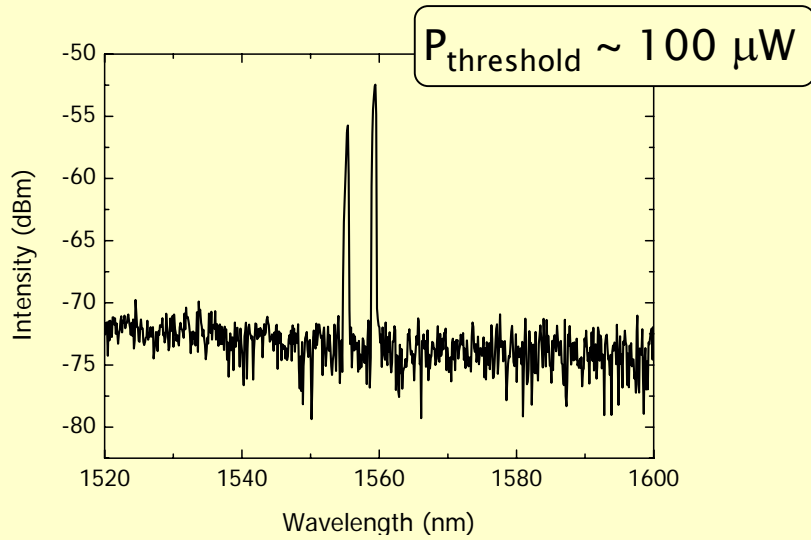
$$R = 29.5 \mu\text{m}$$

PL enhancement due to increased emission onto cavity modes:

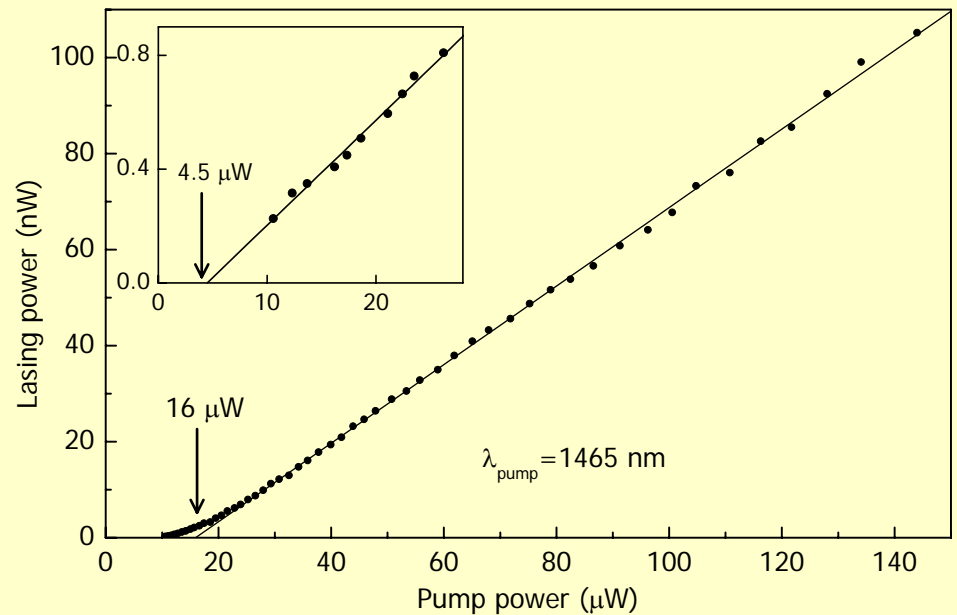
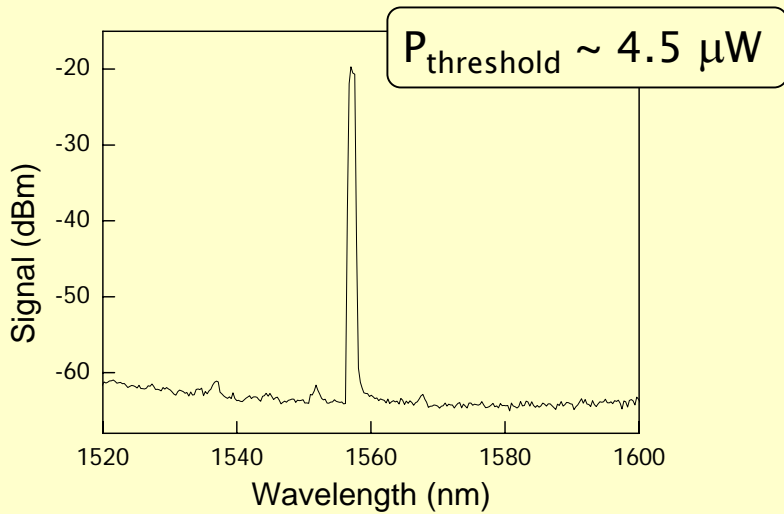
- large fraction of Er not coupled to high-Q modes  $\rightarrow$  Er far from perimeter
- enhancements have low Q  $\rightarrow$  observed from (scattering) losses  
 $\rightarrow$  Er emission linewidth larger than cavity resonance

# Microtoroid lasing I

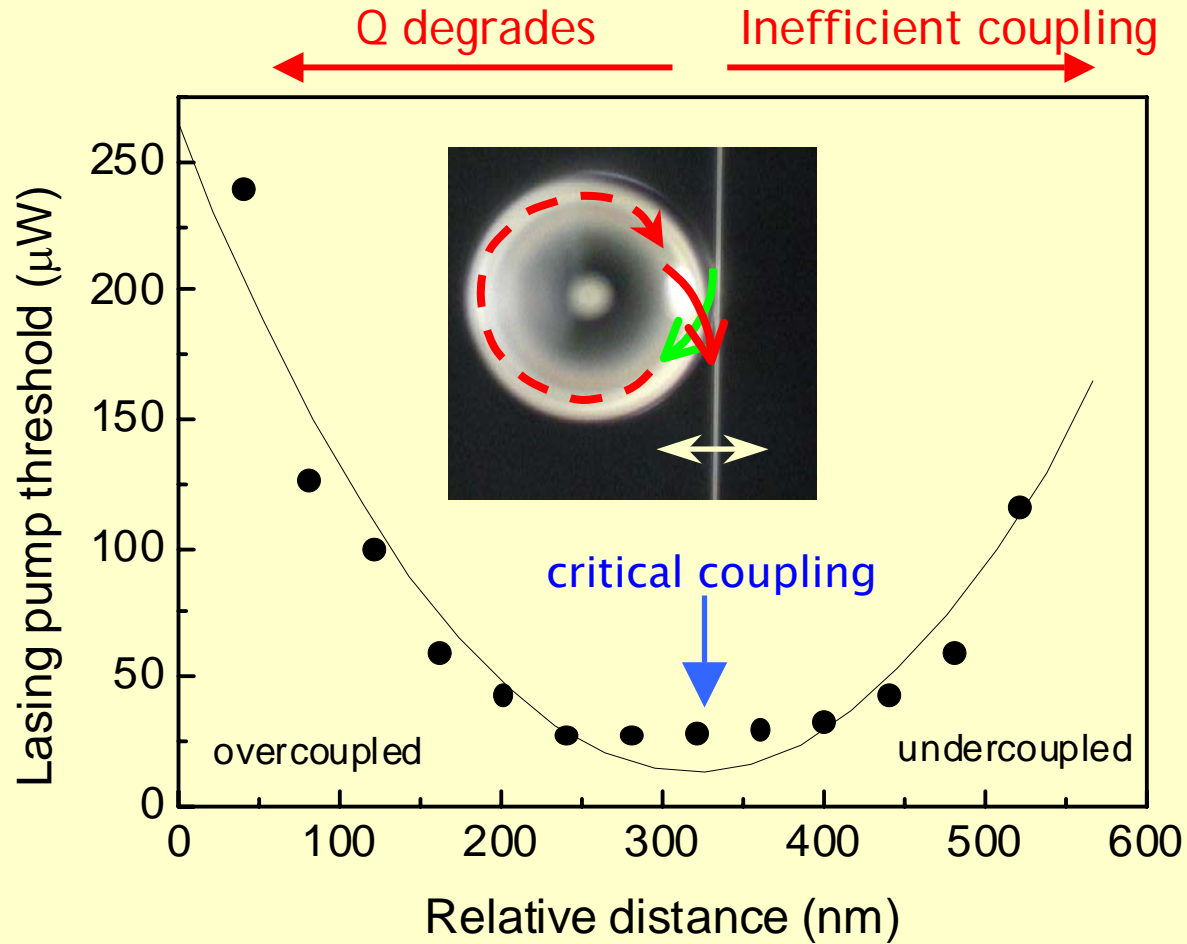
Post-implanted



Pre-implanted

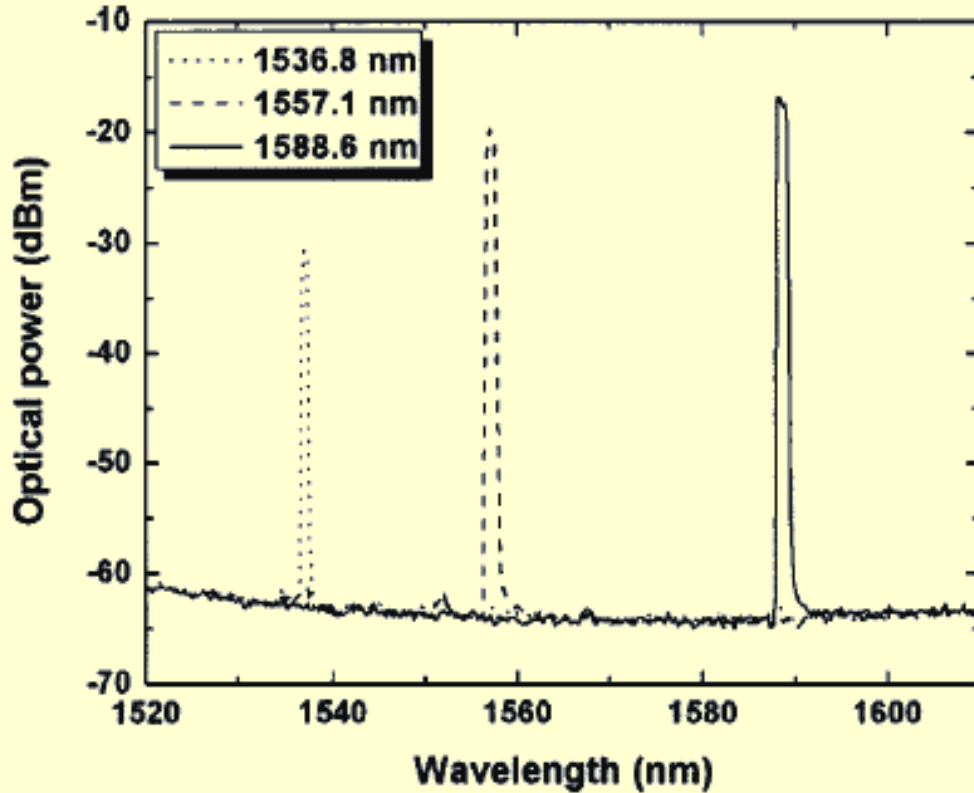


# Microtoroid lasing II

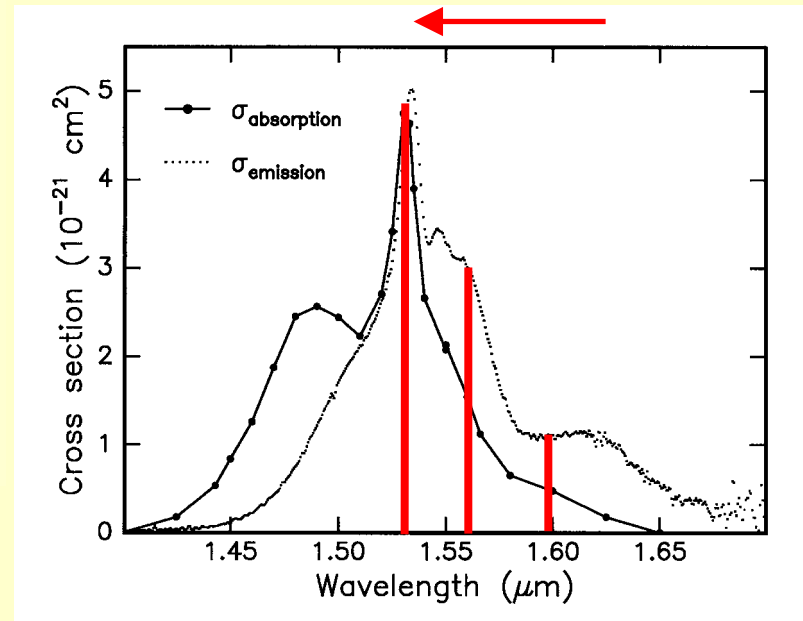


# Microtoroid lasing III

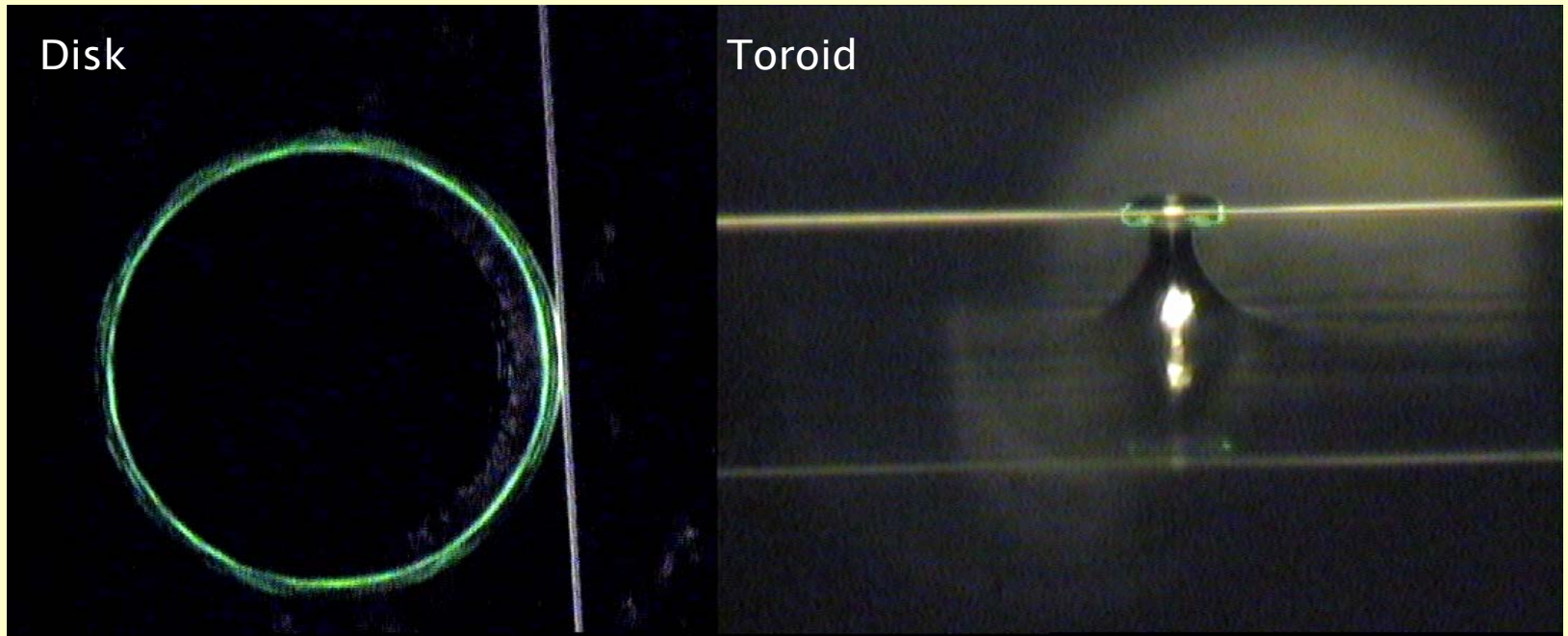
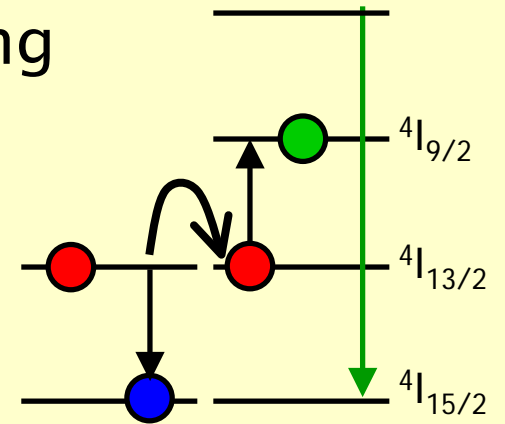
decreasing gap width



gain increase



# Upconversion mode imaging



Er green upconversion emission at high pump powers

# Summary and outlook

## Summary

- Compatibility of ion implantation and high-Q microcavities
- Modified spontaneous emission of erbium
- Low-threshold lasing in microtoroids
- Wavelength tunable laser emission
- Upconversion imaging

## Outlook

- ✘ Er-doped microdisk laser
- ✘ White light pumped Er microcavity laser
- ✘ Si nanocrystal doped microtoroids (scattering, Si lasing)

